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SUSTAINABLE DEVELOPMENT

Assessment of ecological sustainability of a building subjected to potential seismic events during its lifetime

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Abstract

Purpose Sustainable development aims to enhance the quality of life by improving the social, economic and environmental conditions for present and future generations. A sustainable engineering decision-making strategy for design and assessment of construction works (i.e., civil engineering and buildings) should take into account considerations regarding the society, the economy and the environment. This study presents a novel approach for the life cycle assessment (LCA) of a case-study building subjected to seismic actions during its service life, accounting for structural reliability.

Methods A methodology is presented that evaluates the time-dependent probability of exceeding a limit state considering the uncertainty in the representation of seismic action. By employing this methodology, the earthquake-induced damages are related to the environmental and social losses caused by the occurrence of the earthquake. A LCA of a case-study building accounting for the time-dependent seismic reliability is conducted using a damage-oriented LCA approach.

Results and discussion The contributions of the different life cycle phases to the total environmental impact related to the building lifetime are in agreement with previous results in this field of study. However, the LCA results revealed significant risk-based contributions for the rehabilitation phase due to the induced damage resulting in seismic events. Particularly, the rehabilitation phase is expected to contribute to the total environmental impact with around the 25 % of the initial environmental impact load (related to the pre-use phase) as a consequence of seismic damage.

Conclusions and recommendations The probability of occurrence of seismic events affects the LCA results for various life cycle phases of a building in terms of all the indicators adopted in the analysis. The time-dependent probability of collapse in a year can represent a benchmark indicator for human safety in the context of social sustainability for the building sector. The proposed approach can be implemented in a sustainable decision-making tool for design and assessment.

Keywords Life cycle assessment · Limit state probability · Loss assessment · Sustainability · Time-dependent seismic risk

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1 Introduction

The concept of sustainability, as it is known today, has been developed in the 1980s as a result of a process commenced by a group of economists, led by Herman Daly and Robert Costanza in a symposium held in Stockholm in 1984, entitled "Integrating Ecology and Economics" (Jansson 1984). The term "sustainable development" is introduced, as a result of subsequent debates between economists and ecologists, in a report entitled "Our Common Future" (The Brundtland Report 1987). In this report, a sustainable development is defined as a development that "meets the needs of the present without compromising the ability of future generations to meet their own needs". This report quickly became a point of reference for the upcoming issues related to sustainable development. In the next UN conferences (Rio Declaration on Environment and Development 1992; Kyoto Protocol 1997) the concept of sustainable development was further elaborated by discussing the interaction between social development and the environmental awareness. It was established that the international and national policies need to be redirected in order to take into account the environmental and social impact on the world

community having in mind also the future generations. The combination of sustainability and development aims at reconciling the economic growth in the classical sense with modern-day concern for the environment (Meadows et al. 1972). This concept was also underlined by Tiezzi (1984) who claims that one of the main characteristics of contemporary society is the contrast in time-scale between the evolution of the society (fast) and the environmental cycle (slow).

Given the wide range of applicability of the sustainable development, various methodologies and conceptual frameworks have been developed encompassing different disciplines, such as engineering and environmental sciences, economy, business, and social sciences. A framework for sustainability assessment is made up of a set of objectives, sustainable variables/parameters, indicators and performance criteria. The key objectives for sustainable development are generally represented in terms of as a triple-bottom-line strategy illustrated in Fig. 1 (Willard 2002), which is based on simultaneous realization of environmental, economic, and social goals. These objectives are usually established by decision-makers, the community, and the end-users. The sustainability indicators are normally expressed as a function of sustainability variables/parameters in order to describe fairly complex social, economic, and environmental processes (Harrington et al. 1993). Finally, the sustainability criteria are defined in order to verify whether a pre-specified objective has been met.

2 Sustainability in construction industry

Sustainability assessment, in the engineering context, is commonly treated as a multi-criteria multi-objective decision-making problem and is applied to different practical problems, such as, water resource management, transportation, and urban systems (Waheed et al. 2009; Sahely et al. 2005; Foxon et al. 2002). The sustainability objectives can be defined in terms of, for example, minimization of: costs, raw material depletion, energy consumption, land use, waste generation, and greenhouse emissions. Alternatively, they can be defined in terms of maximization of: renewable energy resources, long-term performance, recycling operations, and social acceptance. The set of methodologies, algorithms, and technical tools for rational decision-making under time-varying uncertain circumstances common to the engineering problem-solving (e.g., time- and space-dependent phenomena, probability concerns, changing societal values, climate change) can potentially make a major contribution to the assessment of the sustainable development

In the context of sustainability, the significant role of the construction industry as one of the major exploiters of the environment in the form of, nonrenewable resource depletion, waste generation, energy consumption, and CO_2 emissions, cannot be ignored. It is reported that as much as 40 % of the world material consumption and 30–40 % of the total energy demand and greenhouse gas emissions is related to the building sector, including housing (Huovila et al. 2007; Pulselli et al. 2007; Nässén et al. 2007). Therefore, the construction industry assumes a central role in the quest for reaching a sustainable society within a reasonable period of time. This creates new challenges for engineers; for instance, development of innovative solutions for reducing the use of natural resources, use of renewable resources and minimization of waste generation.

2.1 The typical approach to sustainability assessment

Building sustainability is characterized by the interaction between the built environment and its economic, social, and natural context. In particular, the economic aspects should be considered not only throughout the construction

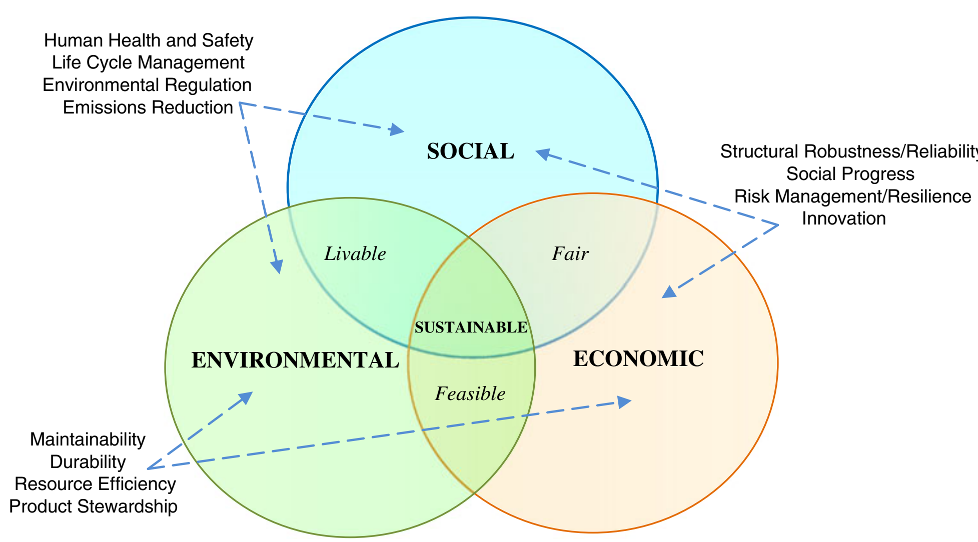

Fig. 1 Triple-bottom-line (TBL) representation and sustainability requirements

phase but also during the service life of the building in terms of building maintenance and preservation. These aspects can be evaluated by employing the "Life-Cycle Cost (LCC)" analysis taking into account both structural performance and energy efficiency criteria (Asprone et al. 2008, Liu et al. 2004; Kneifel 2010). Moreover, systematic economic considerations of all whole life costs and benefits over a certain period of analysis (as defined in the agreed scope) are in general addressed by whole life costing (WLC) methodology, including economic aspects related to capital, facilities management, disposal, performance of building elements and services (El-Haram et al. 2002). The social dimension of sustainability for the built environment is often referred to as socio-political impacts, encompassing various issues such as, social acceptance, equity and opportunity, and adequate planning of social services (e.g., health, education and housing welfare) (Lee et al. 2010; Assefa and Frostell 2007). Other aspects of sustainability in the context of construction works such as intergenerational equity, life quality index, risk acceptance with regard to decision-making, and life-cycle benefit-based design have been discussed by (Faber and Stewart 2003; Faber and Rackwitz 2004). Even though building sustainability is a multi-facet concept, the attention is often focused on environmental aspects. This is due to the large impact of the city metabolism on the natural environment in terms of exploitation of the resources and consumption of energy. The life cycle assessment (LCA) framework, which is used to address issues such as, CO_2 emissions, human health and resource depletion in the decision-making process, is generally adopted in order to quantify the environmental aspects in the construction industry. Life cycle assessment is a technique for quantifying the environmental aspects associated with a product over its entire life cycle, in other words, "from the cradle to the grave". This encompasses the extraction and processing of raw materials, manufacturing, transportation and distribution, use, reuse, maintenance, recycling, and final disposal (Consoli et al. 1993). LCA, employed usually as a decision-making support, is especially suitable for the integration of various life cycle stages in terms of their environmental impact.

The LCA procedure is part of the ISO 14040:2006, *Environmental management—life cycle assessment—principles and framework* (ISO 14040:2006) and ISO 14044:2006, *Environmental management—life cycle assessment—requirements and guidelines* (ISO 14044:2006). An LCA study usually consists of the following four steps:

1. Goal and scope definition: the product, its application and the purpose of LCA study are defined.
2. Inventory analysis: a work flow diagram of the entire life cycle of the product is constructed. This is used as basis for evaluation of the environmental inflow and outflow (e.g., emissions and discharges into the receiving waters, soil, and air) associated to the various life cycle phases.
3. Life cycle impact assessment: this phase aims at quantifying the overall environmental consequences and the resources used. The output of the inventory analysis is used as an input into a framework for life cycle impact assessment (LCIA). In this framework, different impact potentials are calculated and classified into major categories.
4. Interpretation of the results: in this step, the life cycle phases that contribute most significantly to the impact factor categories are identified.

In the context of a LCIA, two alternative methods are used to describe the environmental consequences (Ortiz et al. 2009): (a) problem-oriented methods (a.k.a., mid points), and (b) damage-oriented methods (a.k.a., end points). In the former approach, the environmental flows are directly classified in terms of the environmental impacts (e.g., greenhouse effect, stratospheric ozone depletion, acidification, human toxicity) to which they contribute. In the damage-oriented methods, the environmental impacts are classified and combined into major impact categories. Recalling from the previous paragraph, the major impact categories defined by ISO 14040 are, resource use, ecological consequences, and human health; however, the choice of these categories is specific to the adopted methodology.

The use of LCA in the building industry dates back to the 1990s (Taborianski and Prado 2004; Mora et al. 2011; Gustavsson and Sathre 2006). There are two alternative approaches adopted for the application of LCA to the construction industry (Ortiz et al. 2009; Erlandsson and Borg 2003): (a) LCA for building materials and component combinations (bottom up), and (b) LCA of the whole process of the construction (top down). Moreover, there are commercial software tools, based on the state of practice, available for performing LCA in the building industry (Erlandsson and Borg 2003; Khasreen et al. 2009).

3 Integrating the concept of safety in the framework for sustainability assessment

Given that the sustainability assessment spans over the entire life cycle of a building, it should address all the critical actions to which the structure may be subjected. This is particularly relevant in regions characterized by high risk of natural hazards, such as, earthquakes, hurricanes, tornados, fires, and floods. Moreover, the evaluation of sustainability in building sector is subjected to various sources of modeling uncertainties, such as, the resistance of the infrastructure, material mechanical properties, the duration

of service life, etc. Hence, it is clear that achieving sustainability should entail probabilistic assessment of the safety of the entire system with respect to the critical actions to which it may be subjected. In this context, the safety of a system is measured in terms of the probability of collapse or the mean annual rate of exceeding a specific limit state.

From the environmental point of view, the state of the practice of LCA for buildings is based on the computation of the environmental flows for pre-defined life cycle phases. For instance, the probabilistic assessment of the environmental performance of a building should take into account the uncertainty in the evaluation of the environmental inflow as a result of the hazard-induced damage (related to both construction and end-of-life phases). Given the high social value of constructions, sustainability assessment should also address the social aspects; especially those related to the natural and man-made hazards. Given this consideration, the evaluation of the mean annual probability of collapse for a structure can represent an indirect evaluation of the social worth of sustainability, since it denotes a measure of reliability, robustness and dependability of the structure.

The aim of the present paper is to explore various aspects of the integration of risk assessment procedures in the ecological sustainability assessment of buildings. In particular, LCA of a case-study building has been performed using the IMPACT 2002+ methodology (Jolliet et al. 2003) taking into account the expected loss due to the seismic risk (Fig. 2).

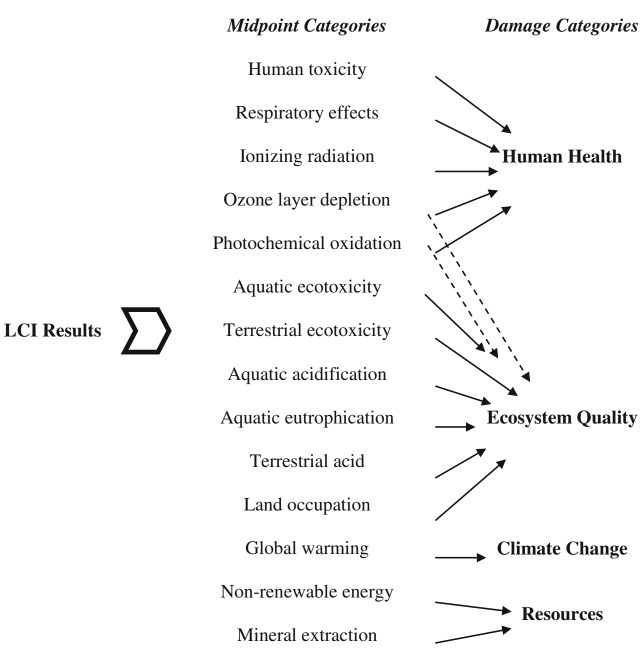

Fig. 2 Scheme of the IMPACT 2002+ framework, linking life cycle inventory (LCI) results via the midpoint categories to damage categories

3.1 Economic, social, and environmental concerns related to seismic risk

The risk-based sustainability assessment of a building encompasses the following general categories/phases: initial construction, damage-based repair and maintenance and final end-of-life replacement. These categories are elaborated in this section from economic, environmental and social point of view.

Studies by (Taghavi and Miranda 2003) investigated the initial cost contribution of different building components. They report that in a typical building, the structural system accounts for approximately 10−20 % of the construction cost. As far as it concerns the nonstructural components, the contribution to initial construction costs depends on the functionality of the building; for instance, a hospital versus a residential building.

Considering the consequences of seismic events on buildings, the resultant damage can affect the structural frame, nonstructural components and building contents. Depending on the induced damage, building components and/or building contents need to be repaired or replaced. In the case of building components, the repair operations may consist in exploiting raw materials, labor and monetary resources. This may cause partial interruption/redirection of the scheduled activities due to the loss of the building function and hence contributing significantly to the overall repair costs. If the building damage is severe and widespread, typical repair operations may not be sufficient. In such case, the building may need to be (a) demolished where its components may be disposed in a landfill or recovered through recycling, and (b) replaced entirely. Hence, given the significance of the damaged-based repair costs, achieving a higher performance level for the building may play a fundamental role in reducing the overall life cycle costs. For example, an increase of about 10 % in the cost of the structural system translates into only a 1–2 % increase in the overall cost of the building but leads to substantially better building performance. The risk-based economic aspect of sustainability, is often quantified in terms of the expected loss, evaluated taking into account various sources of uncertainty, throughout the entire building lifetime as a function of the site-specific seismic hazard, structural performance and induced damage (Goulet et al. 2007; Kircher et al. 2006).

In the initial construction phase, structural components (even though they comprise a small proportion of the total building cost) contribute significantly to the total energy consumed by building due to the large energy required during the manufacturing process and the transportation. Furthermore, the seismic-induced damage significantly affects the environmental performance over the entire lifetime of the building. Hence, the computation of environmental demands during the building lifetime comprises the evaluation of the environmental impacts related to the initial construction, maintenance, and partial/total replacement operations for all of its components.

The evaluation of the social impacts of a building during its life-time is multi-faceted and case-dependent. As much as it regards the social impacts of the seismic-induced damages, the probability of exceeding the collapse (ultimate) limit state can be considered as a proxy for the human life lost. Moreover, the inconvenience perceived by the building inhabitants and the surrounding community is highly correlated to the down-time caused as a consequence of seismic events.

The design and assessment of a structural system is a complex process which balances various aspects related to probabilistic risk analysis, environmental impact, and socio-economic loss assessment. The risk-based economical loss assessment is widely studied in literature; therefore, the present work tends to focus on the environmental aspects in life cycle sustainability. The objective of the methodology presented in this work is to evaluate the life cycle environmental impact for a reinforced concrete (RC) frame building that is subjected to seismic events during its lifetime.

3.2 Methodology

This section presents a step-by-step overview of the methodology introduced in the present work. First, the probabilities of exceeding a set of structural limit states are calculated during the infrastructure's lifetime. Then, the expected life cycle environmental impact indicators are calculated by taking into account the initial construction environmental impact, the additional impact related to the damage and repair operations depending on the damage level and/or the eventual end-of-life/recycling operations The calculations involved in this methodology are based on a presumed specific set of rules for the management of the structure. The methodology presented herein for the evaluation of expected life cycle environmental impact can also be used for decision-making between different seismic upgrading options while satisfying prescribed reliability constraints.

3.3 Multi-hazard assessment of the limit state probability

Let $T_{\max}$ denote the service lifetime of the structure, N the maximum number of critical events that can take place during $T_{\max}$ and τ the repair time for the structure. The probability $P(\mathrm{LS};T_{\max})$ of exceeding a specified limit state LS in time $T_{\max}$ can be written as:

$$P(\mathrm{LS};T_{\max}) = \sum_{i=1}^{N} P(\mathrm{LS}|i)P(i;T_{\max}) \tag{1}$$

where $P(\mathrm{LS}|i)$ is the probability of exceeding the limit state given that exactly i events take place in time $T_{\max}$ (representing the fragility of the system) and $P(i;\ T_{\max})$ is the probability that exactly i events take place in time $T_{\max}$ (representing the site-specific hazard for the system). In order to calculate the term $P(i;\ T_{\max})$, it is assumed that the event/hazard in the lifetime of the structure is expressed by a *Poisson* probability distribution, with a rate of occurrence equal to ν. Thus, the probability of having exactly i events in time $T_{\max}$ can be calculated as:

$$P(i;T_{\max}) = \frac{(\nu T_{\max})^{i} e^{-\nu T_{\max}}}{i!} \tag{2}$$

The term $P(\mathrm{LS}|i)$ is calculated by taking into account the set of mutually exclusive and collectively exhaustive (MECE) events that the limit state is exceeded (for the first time) at event j, j varying between 1 and i. The probability that the limit state is exceeded at event j is calculated by considering that the structure could have been damaged k times, k varying between 0 and $j-1$. Therefore, the evaluation of the term $P(\mathrm{LS}|i)$ requires the evaluation of the set of probabilities denoted by $P(\mathrm{C_j}|k,i)$ that the limit state is exceeded for the first time at event j, given that exactly i events have taken place and as a result of which the structure is damaged exactly k times. The sequence of probabilities $P(C_\mathrm{j}|k,i)$, j=1,…,i and k=0,…, $j-1$, are also referred to herein as the structural fragility terms. The structural fragilities are denoted by $P(\mathrm{C_j}|k)$. It is assumed that if the structure under repair is hit by another event, the repair operations are going to resume from zero. Further details about the adopted methodology are reported in Jalayer et al. (2011).

3.4 Estimation of fragilities

The structural fragilities $P(\mathrm{C_j}|k)$ are calculated as follows:

1. A nonlinear static analysis of the structure subjected to seismic excitation is performed and the result is presented in the form of a static pushover curve (i.e., roof displacement versus base shear). The pushover curve is then transformed into that of an equivalent single degree of freedom (SDOF) structure known also as the equivalent SDOF capacity curve. The onset of different structural limit states is marked on the capacity curve.
2. A suite of M ground motion (GM) records is chosen for the site of the structure. The ground motions may be scaled in order to reflect (in an average sense) the expected intensity of ground motion at the site.

For each k value, k=1,…,$i-1$, repeat steps 3 to 8 below:

3. Each of the ground motion records is transformed into a sequence of k (identical) ground motion records. This is used to emulate the fact that the structure may be damaged k times before being hit by that last event.

4. The equivalent SDOF structure is subjected to the suite of the GM records that are constructed as described in step 3 above.
5. The maximum and residual displacements and the residual strength of the equivalent SDOF system in response to the suite of records are recorded.
6. A linear least squares regression analysis of the (natural logarithm of) SDOF maximum displacement versus (natural logarithm of) earthquake intensity measure (i.e., first-mode spectral acceleration) is conducted in order to estimate the median and the dispersion in the structural response for a given level of ground motion intensity given that the structure is damaged k times.
7. The limit state thresholds marked in step 1 and the median and dispersion estimates obtained in step 6 are used to calculate the structural fragility term $P(C_j|k)$ as a Lognormal cumulative distribution.
8. $k=k+1$ and go to step 3.

3.5 The probability of collapse in a year

In the previous sections, it is explained how the probability of exceeding the limit state LS can be calculated from Eq. (1). It is also of interest to calculate the probability of exceeding the limit state in a year. In general, the probability of exceeding the limit state in the time interval $[T, T+\Delta T]$ can be calculated as:

$$P(\mathrm{LS};[T,T+\Delta T]) = P(\mathrm{LS};T+\Delta T) - P(\mathrm{LS};T) \tag{3}$$

Therefore, the probability of exceeding the limit state in a year can be calculated from Eq. (3), by setting ΔT equal to 1.

3.6 Expected life cycle environmental impact

The expected life cycle environmental impact indicators are calculated from the following equation:

$$E[L;T_{\max}] = E_O + E_R \tag{4}$$

where E_O is the environmental impact of the initial construction phase (calculated deterministically) and E_R is the risk-based repair/replacement environmental impact taking into account the occurrence of the seismic events. The repair contribution E_R can be calculated from the following equation:

$$E_R = \sum_{n=1}^{N_{\mathrm{LS}}} \sum_{t=0}^{T_{\max}-1} L_n e^{-\lambda t} [P(\mathrm{LS}_{n+1};[t,t+1]) - P(\mathrm{LS}_n;[t,t+1])] \tag{5}$$

where $P(\mathrm{LS}_n;[t, t+1])$ is the probability of exceeding the limit state LS_n in the 1-year time interval $[t, t+1]$ from Eq. (3), N_{LS} is the number of limit states ranging from the intact state of the structure up to the limit state of collapse, L_n is the expected environmental impact of restoring the structure from the limit state LS_n back to its intact state including repair operations. In the case of collapse limit state, L_n corresponds to the end-of life replacement. λ is the discount rate which is assumed equal to 0 and the term in the brackets of Eq. (5) is the probability that the structure is between limit states n and $n+1$.

4 Case study

The methodology presented herein is employed for the evaluation of the expected risk-based environmental impacts (the E_R term in Eq. (4)) for the case-study building subjected to earthquakes. The case-study building is a generic five-story RC frame structure with a lifetime of 100 years. The structural model is illustrated in Fig. 3, presenting the plan-view of a generic story. Each story is 3.00 m high, except the second one, which is 4.00 m high. The nonlinear behavior in the sections is modeled based on the concentrated plasticity concept. It is assumed that the plastic moment in the hinge sections is equal to the ultimate moment capacity in the sections which is calculated using the Mander model for concrete (Mander et al. 1998) and elastic–plastic model for steel rebar. The first-mode period of the case-study structure is equal to $T=0.95$ s as reported in a previous work by the authors (Asprone et al. 2008). The sequence of structural limit states LS_n, $n=1$, …., N_{LS} are discretized as: intact, serviceability (operational level), onset of damage (immediate occupancy level), severe damage (life-safety level), and collapse (collapse prevention level). The structural limit states are identified in terms of the maximum displacement of the equivalent SDOF system. The mean annual rate of significant earthquake events is assumed to be equal to $\nu=0.20$ referring to the building site. Figure 4 illustrates the static pushover curve calculated for the examined structure. The displacements

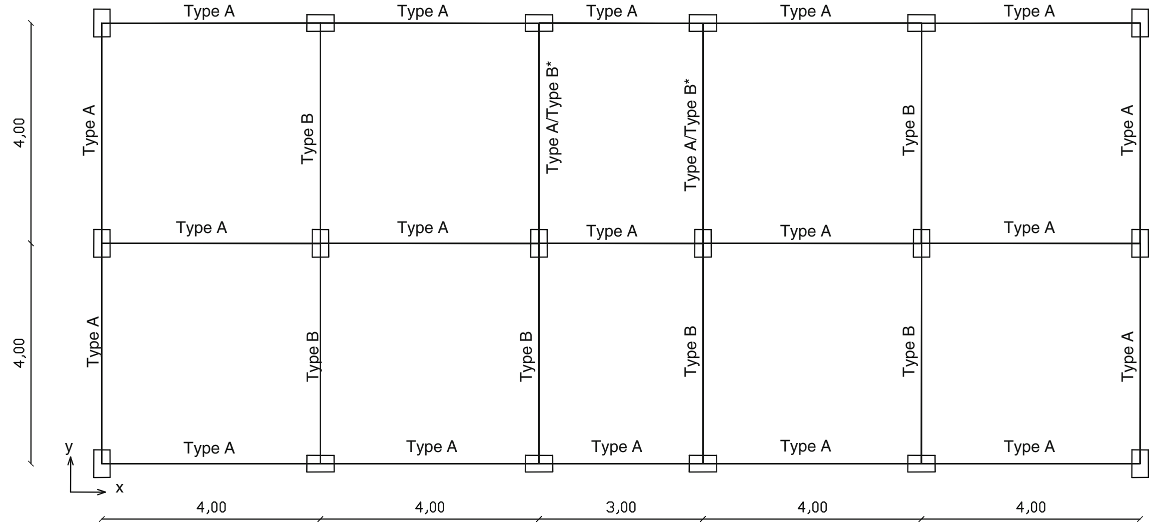

Fig. 3 Story view (dimensions in meters). Beam frame labels indicate the section dimensions in cm; column sections are all (30×30)

marking the onset of different limit states are reported on the figure as circles. Table 1 reports the maximum displacements (as in Fig. 4) for the equivalent SDOF system identifying the serviceability (SR), onset of damage (OD), severe damage (SD), and collapse (CO) limit states for structure. The seismic fragilities are calculated based on the procedure described in the previous section by selecting a set of ground motion records and applying it to the equivalent SDOF system.

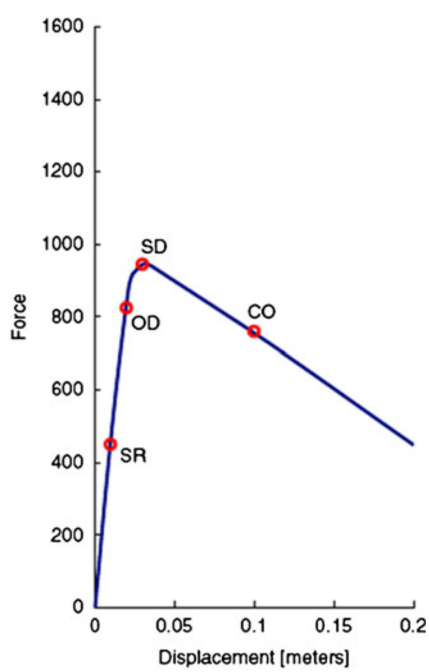

Fig. 4 Pushover curves for the equivalent SDOF system: *CO* collapse, *SD* severe damage, *OD* onset of damage, *SR* serviceability

4.1 Damage evaluation

Evaluation of the seismic damage must take into account the performance of both structural and nonstructural components. In order to map out each limit state threshold to overall levels of structural and nonstructural damage, the FEMA specifications (FEMA 273 1997) are used as a reference. The general structural and nonstructural components damage classification for each limit state is reported in Table 2. The "component by component" damage description corresponding to each limit state and the damage classification in Table 2 is applied to: vertical elements, horizontal elements, architectural components, mechanical–electrical–plumbing systems/components, and building contents. As an example, Table 3 reports the glazing damage occurring at the different limit states. All these information have been taken into account in order to evaluate the expected damage and the related risk-based environmental impact during the lifetime of the case-study building.

4.2 Life cycle assessment of the case-study building

The LCA of the case-study building has been performed on the basis of the results reported in (DEQ 2010). The present

Table 1 Equivalent SDOF maximum displacement (m)

LS	Equivalent SDOF maximum displacement (m)
Serviceability	0.01
Onset of damage	0.02
Severe damage	0.03
Collapse	0.10

Table 2 Occurred damage related to the performance level

	Serviceability (operational level)	Onset of damage (immediate occupancy level)	Severe damage (life-safety level)	Collapse (collapse prevention level)
Overall damage	Very light	Light	Moderate	Severe
General	No permanent drift; structure substantially retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. All systems important to normal operation are functional	No permanent drift. Structure substantially retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. Elevators can be restarted. Fire protection operable	Some residual strength and stiffness left in all stories. Gravity-load-bearing elements function. No out-of-plane failure of walls or tipping of parapets. Some permanent drift. Damage to partitions. Building may be beyond economical repair	Little residual stiffness and strength, but loadbearing columns and walls function. Large permanent drifts. Some exits blocked. Infills and unbraced parapets failed or at incipient failure. Building is near collapse
Non structural components	Negligible damage occurs. Power and other utilities are available, possibly from standby sources	Equipment and contents are generally secure, but may not operate due to mechanical failure or lack of utilities	Falling hazards mitigated but many architectural, mechanical, and electrical systems are damaged	Extensive damage

study considers as functional unit the provision of 100 years of housing for the case-study building (described in Section 4.1). The main goal of the assessment is to quantify the expected (potential) environmental loads related to seismic events which may potentially occur throughout the entire building lifetime and compare these results with the environmental loads/consequences related to the other different life cycle phases of the building. This goal is attained through the following procedure consisting of specific objectives:

– Create a LCA model for the case-study where system boundaries are defined and building components are grouped into categories to which a mechanical and environmental performance is correlated;
– Identify different limit states and the corresponding levels of damage for the different categories of building components (as explained in Section 4 and 4.1 respectively);
– Relate the damage occurring for the different limit states and affecting the different categories of the building components to the environmental loads;
– Evaluate the total expected environmental load associated with the occurrence of seismic events, on the basis of the probabilistic approach reported in Section 3.6, by means of Eq. (5);
– Perform the assessment according to a defined methodology to analyze and quantify the environmental consequences related to the case-study, during its whole life cycle.

The boundaries of the study are intended to include all impacts within the production chain of the used materials, energy and processes that comprise the building life cycle. In particular, the current assessment accounts for the production and manufacture of all materials including the structure of the building (the original and replacement materials), the transportation of these materials to and from the building site, the construction operations, maintenance of the whole structure, the use of the home (including heating and cooling energy, electricity use, and water use/heating), its demolition and disposal. In particular, in order to include the total environmental impacts, the life cycle phases analyzed in the present study are grouped into four principal phases:

- *Pre-Use*: production of original materials, transportation, construction operations
- *Occupancy* (use): heating and cooling, electricity use, water use
- *Occupancy* (maintenance): production of replacement materials, transportation, maintenance operations
- *Post-Use*: dismantling/demolition, end of life

Table 3 Occurred damage related to the performance level: glazing case

Operational level	Immediate occupancy level	Life-safety level	Collapse prevention level
Some cracked panes: none broken	Some cracked panes: none broken	Extensive cracked glass; little broken glass	General shattered glass and distorted frames. Widespread falling hazards

Moreover, for the purpose of the study and for the scheme of the proposed assessment, the building materials/components are divided and grouped into the following categories:

- Foundation
- Super structure: RC frame, Roof
- Nonstructural: Siding, Insulation, Interior, Trim, Door/Windows
- Water and electrical systems: Water, Trim, Ducting
- Major appliances

The LCA data for this work were collected from different databases (Hedemann and König 2007; IDEMAT 2001). It is underlined that the study has been conducted using an assembly based pattern; to do this DEQ 2010 data have been considered for the life cycle inventory. Further details of the assumptions made for the assessment and boundaries adopted are reported in DEQ 2010.

According to the damage descriptions corresponding to different limit states (FEMA 273 1997), for each limit state and for each building component category, it is assumed that the amount of new materials (and also the entity of transportation and construction operations) needed for restoring the original state of the building is computed as a percentage in weight of the quantities needed for initial construction (Table 4). As an example, the elevation structures, as reported in Table 4, may require an amount of additional materials and overall operations which is equal to 0, 15, 60, and 100 % in weight of the initial ones in correspondence of SR, OD, SD, and CO limit states, respectively. Hence, the environmental load related to the computed new quantities is assessed by means of the common procedure of LCA, i.e., through the selected databases. It should be noticed that other sources of potential environmental impact related to the "unavailability" of the building as a consequence of seismic event are not taken into account in the present study. Following the proposed approach, these computed environmental loads are not taken as they are in light of the goal of the assessment, but they are treated according to the probabilistic methodology described in Section 3.6. In other words, the new computed environmental loads are multiplied by the probability of exceeding each limit state in a year (triggering an expected damage to the building), then summed up over all the limit states and finally integrated in time over the life span of the case-study building, as in Eq. (5). The outcomes of this procedure represent the (potential) environmental loads associated to the building rehabilitation which are expected to be generated during the entire life span as a consequence of the occurrence of seismic events in that period of time.

Hereby, in addition to the above-mentioned life cycle phases, an additional phase called as *Rehabilitation Phase* is considered in order to take into account the replacement/repair operations and raw materials, needed to restore the damaged building, as explained before.

Finally, in order to estimate the environmental performance of the structure under examination, the IMPACT 2002+ (Jolliet et al. 2003) methodology was adopted which links all types of life cycle inventory results (elementary flows and other interventions) via 14 midpoint categories (illustrated in Fig. 2) into four damage endpoint categories described as follows:

– *Climate change* (CC): or global warming potential; substances known to contribute to the global warming are weighted based on an identified global warming potential expressed in kilograms of carbon dioxide equivalents ($KgCO_2e$).
– *Human health* (HH): it is a measure of the damage caused by the release of substances that affect human beings through toxicity, respiratory effects, UV radiations, and others. These substances are weighted based on their ability to cause a variety of damages to human health. The meter used for measuring this kind of impact is the disability-adjusted life years (DALYs), which

Table 4 Percentage of material components needed for the building rehabilitation depending on the limit state level

	Operational (%)	Immediate occupancy (%)	Life safety (%)	Collapse prevention (%)
Foundation structures	0	0	30	100
Elevation structures	0	15	60	100
Nonstructural	15	35	80	100
Water and electrical systems	0	20	75	100
Major appliances	0	10	50	100

combines the resulting injuries and mortality rates into a single factor expressing an overall reduction in the life expectancy.

– *Ecosystem quality* (EQ): it measures the potential damages affecting the health of an ecosystem through the release of substances that cause acidification, eutrophication, toxicity to wildlife, land occupation etc. These impacts are measured in units of potentially disappearing fractions, which is expressed in term of the probability of species loss.
– *Resource depletion* (RD): this damage category measures the depletion generated by the mineral extraction, nonrenewable resources consumption and over-use renewable resources (i.e., the consumption rate larger than renewal rate). Materials are weighted based on their abundance and facility to access. These environmental impacts are measured in megajoules expressing the amount of energy required to obtain an additional amount of the considered substance from the earth.

Since the goal of the study is to evaluate the role of potential environmental impacts in the rehabilitation phase (related to the building lifetime), the LCA results has been handled in terms of end point categories. In this way a more appreciable understanding of potential environmental consequences is possible since an effective comparison with the typical environmental building contributions can be performed.

5 Discussion

The LCA results are illustrated in Fig. 5. As found in prior LCA results on housing (Scheuer and Keoleian 2002; Peuportier 2001), the major amount of the environmental impacts related to the entire lifetime of the house is due to the use of energy during occupation phase (between 50 and 70 %). The normal use of a house (which includes consumption of heating fuel, water and electricity) is clearly the most prominent phase in the life cycle for all the four environmental impact categories studied. It should be mentioned that the sub-categories of the life cycle phases (such as transportation and construction related phases etc.) are not reported in a disaggregated manner since they contribute a relatively small amount (an overall contribution of 6 % or less).

Material production, both as the original (pre-use phase) and as replacement materials (maintenance phase) has a significant contribution (slightly higher than 40 %) in the case of RD and HH impact categories. For other impact categories, the contribution of pre-use and maintenance phase is in the range of 25 to 30 % (CC and EQ). The end-of-life phase is relatively insignificant, for the majority of impact categories.

Figure 6 illustrates the LCA results in the Pre-Use phase for the four environmental impact categories disaggregated into building components. The major contributions come from the structural elements (super structure) and nonstructural components ranging between 30 % (super structure for EQ impact category) and 41 % (super structure for RD impact category). The remaining building components contribute to a lesser extent with roughly 10 % for each type of building component and in each impact category. The LCA results demonstrate significant risk-based contributions for

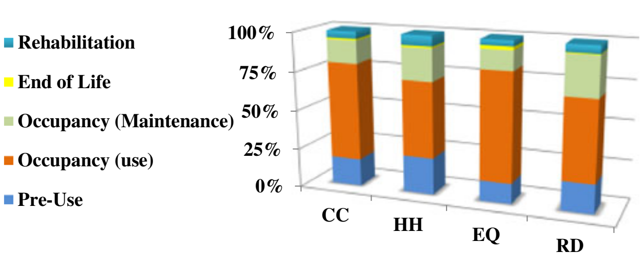

Fig. 5 LCA results for the four damage categories: *CC* climate change, *HH* human health, *EQ* ecosystem quality, *RD* resource depletion

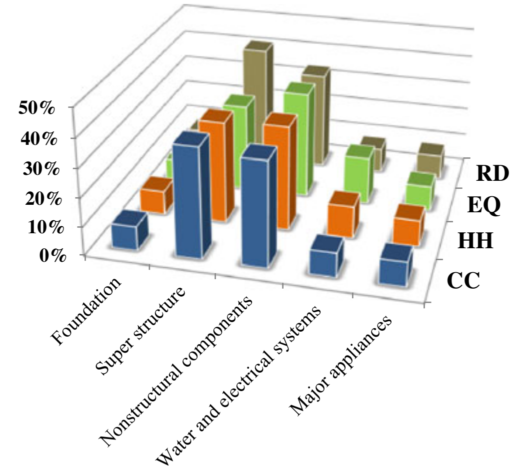

Fig. 6 LCA results for the building components: *CC* climate change, *HH* human health, *EQ* ecosystem quality, *RD* resource depletion

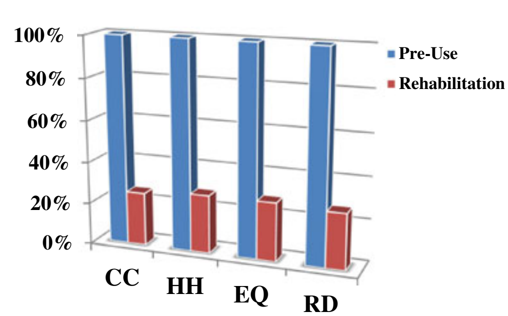

Fig. 7 LCA results comparing the rehabilitation phase and pre-use phase: *CC* climate change, *HH* human health, *EQ* ecosystem quality, *RD* resource depletion

the rehabilitation phase due to the seismic events: in the case of HH impact category, the predicted impact associated to the rehabilitation phase reaches 6.5 % of the overall impact. A comparison between the rehabilitation phase and pre-use phase is proposed in Fig. 7: around 25 % of the initial environmental impact (reported as 100 %) is expected to be a consequence of seismic damage occurring during the entire building lifetime. It should be remarked that the data obtained for the rehabilitation phase have been computed as averaged values throughout the service life and are strongly dependent on the seismic performance of the building. Hence, the environmental impact of a particular structural and/or nonstructural design choice can be regarded as a benchmark variable in decision-making problems in a sustainable development context.

6 Concluding remarks and recommendations

This paper presents a preliminary effort for the sustainability assessment of structures subjected to seismic risk. A methodology is proposed for probabilistic life cycle assessment of the structure taking into account the seismic risk-based time-dependent expected loss. The time-dependent probability of collapse in a year, which is used as a proxy for life-safety/reliability considerations, is calculated taking into account the residual damage due to the sequence of earthquake events and the uncertainties in the seismic action during the service life of the building. The analysis revealed that the probability of occurrence of seismic events influences the LCA results for various life cycle phases of a building in terms of all four indicators. It constitutes around 6 % of the total environmental impact and around 25 % of impact compared to the initial construction phase.

As a final point, authors want to emphasize the following issue. Actually, social sustainability in case of seismic events is of particular concern and the risk to human life and social disruption from earthquakes are crucial factors for decision-makers and political strategists (Comerio 2004). A review of the consequences of several large earthquakes demonstrates that the damage is typically concentrated in buildings. In particular, the residential sector constitutes as much as 90 % of the total number of buildings damaged and as much as 50 % of the total losses due to buildings damage (Comerio 1997a; Comerio 1997b). The social aspects of sustainability can be related to structural performance in terms of probability of collapse as a proxy for human safety.

Focusing on the limit state of collapse CO, the probability of exceeding the collapse limit state in a year can be calculated by differentiation of $P(\mathrm{LS}|\ t)$ with respect to time as stated in Eq. (4). The annual probability of collapse can represent an indicator for social sustainability accounting for human safety. It should be re-emphasized that this indicator is strictly related to the seismic performance of the building. Moving from this consideration, a total sustainability assessment, also accounting for social and economical (by means of LCC and WLC analysis) aspects, can represent a further development of the proposed methodology.

Finally, the present study highlights the need for a multi-criteria and multi-disciplinary decision-making process that encompasses the design of structural systems, seismic hazard analysis, architectural considerations, local practices and the choice of building materials. The authors believe that the awareness of the relationship between risk, environment, and society with the common goal of reaching sustainable development should become a prerequisite for practitioners and operators in the construction industry.

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